P1 1189179

THE UNITED STATES OF AMERICA

TO ALL TO WHOM THESE PRESENTS SHALL COME:

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office

July 01, 2004

THIS IS TO CERTIFY THAT ANNEXED HERETO IS A TRUE COPY FROM
THE RECORDS OF THE UNITED STATES PATENT AND TRADEMARK
OFFICE OF THOSE PAPERS OF THE BELOW IDENTIFIED PATENT
APPLICATION THAT MET THE REQUIREMENTS TO BE GRANTED A
FILING DATE.

APPLICATION NUMBER: *60/473,842*
FILING DATE: *May 28, 2003*
RELATED PCT APPLICATION NUMBER: *PCT/US04/09645*

By Authority of the
COMMISSIONER OF PATENTS AND TRADEMARKS
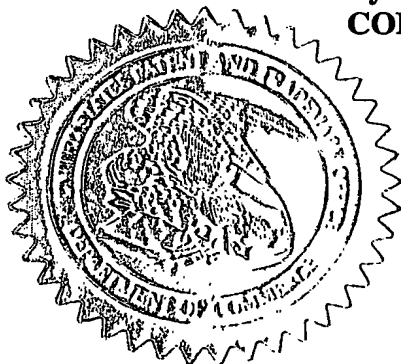
M. SIAS
Certifying Officer

PRIORITY DOCUMENT
SUBMITTED OR TRANSMITTED IN
COMPLIANCE WITH
RULE 17.1(a) OR (b)

BEST AVAILABLE COPY

PROVISIONAL APPLICATION COVER SHEET [37 CFR 1.53(c)]

This is a request for filing a PROVISIONAL APPLICATION under 35 U.S.C. §111(b) and 37 CFR 1.51(a)(2)

Date   : May 28, 2003
Docket No. : 50333/FLC/R268
EXPRESS MAIL NO. EV 352374704 US

Mail to: Mail Stop PROVISIONAL PATENT APPLICATION

INVENTOR(S)/APPLICANT(S) (LAST NAME, FIRST NAME, MIDDLE INITIAL, RESIDENCE (CITY AND EITHER STATE OR FOREIGN COUNTRY)

Gerla, Mario, Santa Monica, California and Sanadidi, M. Yahya , Santa Monica, California

_____ Additional inventors are being named on separately numbered sheets attached hereto.

TITLE OF THE INVENTION (280 characters max)

TCP WINDOW CONGESTION CONTROL

APPLICANT(S) STATUS UNDER 37 CFR § 1.27

__X__ Applicant(s) and any others associated with it/them under § 1.27(a) are a SMALL ENTITY

ENCLOSED APPLICATION PARTS

__14__ Specification (number of pages)
__6__   Drawings (number of sheets)
_____ Assignment
__X__   Other (specify): Appendices A-D

FEE AND METHOD OF PAYMENT

__X__ A check for the filing fee of $ 80.00 is enclosed.
The Commissioner is hereby authorized to charge any fees under 37 CFR 1.16 and 1.17 which may be required by this filing to Deposit Account No. 03-1728. Please show our docket number with any charge or credit to our Deposit Account. **A copy of this letter is enclosed.**

_____ No filing fee enclosed.

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

_____ No   __X__ Yes, the name of the U.S. Government agency and the Government contract number are: ANI-9983138

Please address all correspondence to **CHRISTIE, PARKER & HALE, LLP, P.O. Box 7068, Pasadena, CA 91109-7068, U.S.A.**

Respectfully submitted,

CHRISTIE, PARKER & HALE, LLP

By _____
Frank L. Cire
Reg. No. 42,419
626/795-9900

PROVISIONAL APPLICATION FILING ONLY

FLC/sd
SD PAS506708.1-*-5/28/03 6:11 AM

TCP WINDOW CONGESTION CONTROL

5   STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

10   BACKGROUND OF THE INVENTION

This invention pertains generally to data transmission protocols and more specifically to moderating transmission rates in the presence of congestion.

The Transmission Control Protocol (TCP) provides end-to-end,
15   reliable, congestion controlled connections over the Internet. The congestion control method used originally in TCP Tahoe included two phases: slow-start and congestion avoidance. In TCP Reno, recovery from sporadic packet losses is enhanced by fast retransmission and fast recovery. SACK-based TCPs provide the
20   sender with more complete information about which packets are lost. Another class of algorithms is referred to as "NewReno" which does not need SACK information and requires only modification on the sender side. Research shows that the majority of TCP implementations are NewReno. Therefore, TCP Westwood and
25   its refinement variants were implemented with NewReno as a base.

Increasingly, TCP is called upon to provide reliable and efficient data transfer over a variety of link technologies including wired and wireless with increasing bandwidth capacity. The new ultra high speed wired/wireless environment is exceeding
30   the range for which TCP was initially designed, tested and tuned. As a consequence, active research is in progress to extend the domain of effective TCP operability. The use of path conditions estimate for enhancing congestion control in TCP has been proposed, termed TCP Vegas. In TCP Vegas, the sender infers the
35   network congestion level from observed changes in Round Trip Time

(RTT). If RTT becomes large, the source will decrease its congestion window (cwnd), thus reducing its transmission rate.

5   However, new arriving connections to a congestion in progress may not be able to get a fair share of the bottleneck bandwidth. In a packet pair scheme, a sender estimates the bottleneck backlog and adjusts its sending rate accordingly. However, the packet pair scheme explicitly assumes round-robin scheduling at the

10   routers - a feature not available in many commercial routers. Several network and link-layer enhancements have also been proposed to improve TCP performance under various conditions (congestion loss, random loss, handoff, out of order delivery, etc.), such as random early detection , Explicit Congestion

15   Notification (ECN), and Explicit Loss Notification (ELN).

TCP Westwood design adheres to the end-to-end transparency guidelines and requires only sender side modification. The key innovation of TCP Westwood is to use a bandwidth estimate directly to drive a congestion window (cwin) and a slow start

20   threshold (ssthresh) settings. The current estimation method in TCP Westwood is based on Bandwidth Estimation (BE). This TCP Westwood BE strategy provides significant throughput gains, especially the large leaky pipes. However, under certain congestion circumstances, BE exceeds the fair share of a

25   connection resulting in possible unfriendliness to TCP New Reno connections.

Therefore, a need exists for a cwin and ssthresh setting method for TCP Westwood that reduces a TCP Westwood process's tendency to exceed its fair share of a connection. Various

30   aspects of the present invention meet such need.

FEATURES

In one aspect of the invention, ACKnowledgments (ACKs) are used to estimate a connection rate share. The estimate of

35   connection rate share is then used to directly set congestion

control parameters to provide highly efficient congestion control.

In another aspect of the invention, a rate sample is obtained when an ACK arrives using information in the ACK regarding the delivered bytes and the last two ACKs inter-arrival time. The he samples are then exponentially averaged to produce smoothed rate estimates using a filter with time varying coefficients.

In another aspect of the invention, two estimators are maintained by a transmission control process to set cwin and ssthresh. The transmission control process uses the estimators to identify the predominant cause of packet loss using a Loss Discrimination Algorithm (LDA). The LDA relies on a ratio of expected throughput to achieved throughput. If this ratio exceeds a threshold (a parameter of this method), the LDA declares the packet loss to be resulting from congestion and therefore chooses an estimate based on an interval of length T, which is another parameter of this method. If on the other hand, the ratio of expected to achieved throughput is below the threshold, the loss is assumed to be the result of an error, and the sample interval is taken to be the last ACK inter-arrival time. The samples are exponentially averaged and filtered to produce smoothed eligible rate estimates. Depending on the outcome of the LDA, the appropriate estimator is used to set cwin and ssthresh. Both estimators use information obtained from ACKs received at the sender. One estimator BE, as in standard TCP Westwood, considers each ACK pair separately to obtain a bandwidth sample, filters the samples into a low-pass filter and returns as a result the available bandwidth that the TCP connection is estimated to be getting from the network. The other estimator, herein termed Rate Estimator (RE), considers the amount of data acknowledged during the latest interval of time T as sampled, then feeds such samples into an appropriate low-pass filter to get the estimated rate,

in this case tending to estimate the throughput that the TCP
Westwood connection has recently experienced. This method of
using two estimators is herein termed Combined Rate and Bandwidth
estimation (CRB).

In another aspect of the invention, the CRB method uses the
relationship between the current cwin value and the estimated
pipe size, the latter indicated by the product of RE and a
minimum RTT (RTTmin). When RE * RTTmin is significantly smaller
than cwin, it is more likely that packet losses are due to
congestion. This is because the connection is using a cwin value
much higher than its share of pipe size, thus congestion is
likely. In CRB, whenever a packet loss is indicated, the sender
determines the predominant cause of loss as follows: when the
ratio RE *RTTmin to cwin exceeds a threshold value θ, the use of
RE is indicated. Below θ, BE is indicated.

In another aspect of the invention, a packet loss is
indicated either by a reception of 3 duplicate ACKs (DUPACKs) or
a coarse timeout. The CRB method sets ssthresh and cwin after
a packet loss indicated by three DUPACKs. If cwin divided by
RE * RTTmin divided by the TCP segment size is greater than θ,
then a congestion condition is indicated and ssthresh is set to
RE* RTTmin divided by the TCP segment size. Otherwise, ssthresh
is set to BE * RTTmin divided by the TCP segment size. After
ssthresh is adjusted, then cwin is compared to ssthresh. If cwin
is greater than ssthresh then cwin is set to ssthresh.

In another aspect of the invention, an adaptive method is
used to estimate the rate a connection is eligible to use. The
estimation is adapted to the perceived congestion level in such
a way that the resulting estimate, herein called "Eligible Rate",
provides both higher efficiency as in the method above, as well
as friendliness to other traffic types sharing the network path.
Under packet loss because of congestion, the resulting eligible
rate estimate is conservative, and thus improves friendliness by

accommodating other traffic types sharing the network resources. Under low congestion, a packet loss is assumed to be the result
5   of random error. The resulting eligible rate estimate is more aggressive, improving efficiency under random loss.

In another aspect of the invention, herein termed Adaptive Bandwidth Share Estimation (ABSE), the sample interval T is continuously adapted to the perceived network congestion level.
10   The sample interval can be as small as the latest ACK inter-arrival time, and can grow in a continuous manner up to the estimated minimum round trip time of the connection. The congestion level is determined from the difference between the expected throughput and the achieved throughput of the
15   connection. The samples are exponentially averaged and filtered to produce the eligible rate estimate. The eligible rate estimate is then used to set cwin and ssthresh as before.

BRIEF DESCRIPTION OF THE DRAWINGS
20   These and other features, aspects, and advantages of the present invention will become better understood with regard to the following description, accompanying drawings, and attached appendices where:

FIG. 1 is an equation for a current rate estimator in
25   accordance with an exemplary embodiment of the present invention;

FIG. 2 is an equation for a rate estimator for a previous rate estimator in accordance with an exemplary embodiment of the present invention;

FIG. 3 is an equation for a current rate estimator using a
30   previous rate estimator in accordance with an exemplary embodiment of the present invention;

FIG. 4 is an equation for a filtered rate estimator in accordance with an exemplary embodiment of the present invention;

FIG. 5 is a pseudocode listing for a TCP control process in
35   accordance with an exemplary embodiment of the present invention;

FIG. 6 is a block diagram of a computing device suitable for hosting a transmission protocol control process in accordance with an exemplary embodiment of the present invention;

5   FIG. 7 is a pseudocode listing for a TCP control process using an adaptive bandwidth share estimate in accordance with an exemplary embodiment of the present invention;

Appendix A is a publication describing a first method of

10   calculating a BE in accordance with an exemplary embodiment of the present invention;

Appendix B is a publication describing simulation results of an investigation of an exemplary embodiment of the present invention;

15   Appendix C is a publication describing an adaptive bandwidth share estimation process in accordance with an exemplary embodiment of the present invention; and

Appendix D is a publication describing a specific implementation of the present invention.

20

DETAILED DESCRIPTION

To identify the predominant cause of packet loss, ECN and ELN can be used. However, ECN requires all the routers along a network path to support ECN, while ELN has its share of

25   implementation problems as reported in.   Instead, a method to identify the predominant cause of packet loss may be used that does not require support from lower layers. The method uses the relationship between the current congestion window value and the estimated pipe size, the latter being defined as the product of

30   RE and the minimum RTT observed. The pipe size corresponds to the ideal window required to achieve the rate RE. When the measured pipe size is significantly smaller than cwin, it is very likely that packet losses are due to congestion.

TCP design aims to utilize all available bandwidth, while

35   maintaining "fairness" in the allocations made to different flows.

Fairness is achieved by equally allocating the available
bandwidth to active TCP flows, unless some of them are inherently
5   unable to use their share regardless of the existence of
competing flows. For instance, on a "leaky" large pipe, NewReno
utilization is dramatically reduced. In this case, a flow using
a new proposed protocol can achieve higher bandwidth share and
preserve fairness. However, this should be accomplished without
10   reduction in the legacy connections throughput. Fair bandwidth
share may be defined for the following cases:

   a) for N TCP Westwood flows sharing a bottleneck link with
   capacity C, rhe fair share is C/N;

   b) for a total of N TCP Westwood and TCP NewReno flows,
15   assuming that no random errors are possible, both protocols
   are roughly equivalent, and therefore the fair share for
   each flow is C/N;

   c) Assuming that there are random errors on the paths (e.g.
   from a wireless link) to which all flows are subjected.
20   Because TCP NewReno flows are inherently unable to utilize
   the link capacity in this case, TCP Westwood flows should
   not be considered aggressive by getting a larger bandwidth
   share than the NewReno flows. We define the fair share of
   a NewReno flow as the same value if all flows are TCP
25   NewReno. For instance, suppose the fair share of the NewReno
   flow is Sr given that there are total N homogenous TCP
   NewReno flows, then when this total N flows includes some
   TCP Westwood flows, the fair share of NewReno flow should
   remain Sr, while TCP Westwood flows could have a fair share
30   of higher value. Thus, a TCP Westwood fair share can be
   higher than a NewReno share since the latter connection is
   inherently incapable of using the link capacity.

   d) In the presence of non-adaptive high-priority flows (e.g,
   real time streaming traffic) which take away a portion of
35   bandwidth determined by their transmission rates, we just

reduce the capacity available to TCP connections by the amount used by the non-adaptive flows and proceed to calculate fair share of a TCP Westwood connection as in the above three cases.

In TCP Westwood, the BE estimator is used to drive cwnd and ssthresh determination. This protocol has been shown to achieve a high utilization when used over large leaky pipes. In certain cases, BE may overestimate its fair share. In this case, TCP NewReno (and other TCP-like protocols) may experience performance degradation. TCP Westwood Rate Estimation (RE) addresses the issue of friendliness to NewReno. Both estimations are based on the ACK arrival process received by the TCP-W sender; thus, they are passive and introduce no extra link overhead.

A TCP Westwood sender uses ACKs to estimate BE. More precisely, the sender uses the following information: (1) the ACK reception rate; and (2) the information an ACK conveys regarding the amount of data recently delivered to the destination. For details regarding the processing of ACKs in (2), please refer to APPENDIX A.

Significant efficiency improvements are obtained using the BE estimator produced by the sampling and filtering methods above. This is particularly true in environments with large leaky pipes. Further, note that when routers employ around robin policy in scheduling transmissions, BE is accurate in estimating a connection fair share. However, for drop-tail routers, since TCP traffic tends to be "bursty", i.e. sending out a full window of packets and then waiting for the acknowledgments, BE may over-estimate the connection fair share.

Consider an alternative bandwidth sample, defined as the amount of data reported to be delivered by all ACKs that arrived in the last T time units, divided by T. This method is herein termed Rate Estimation (RE). This alternative is identical to

-8-

the earlier TCP Westwood sample definition if the ACKs are uniformly spaced in time. Simulation and measurements, however,

5   show that ACKs tend to cluster in bursts. Thus, the BE sampling method "overestimates" the connection fair share, while providing (in the bursty case) a reasonably good estimate of the available bandwidth at the bottleneck. Thus, BE is more effective in environments with random error, and when single connection

10   efficiency is paramount.

The RE sample associated with the kth received ACK is expressed by the equation in FIG. 1, where: dj is the amount of data reported by ACK j. Similarly, at the previous time instant, k-1, the sample k-1 is given by equation in FIG. 2. Therefore,

15   the RE associated with the kth received ACK can be determined from the RE associated with the k-1 received ACK as given in the equation in FIG. 3. Thus, at any instant, a sliding window of length T is used to obtain a bandwidth sample.

The expression above is a recursive one, because the sample

20   is calculated using its previous value as reference. Additionally, the technique places equal emphasis on all data points in the sampling range. Thus a value in the near past will have the same influence as a more current measurement when calculating the sample. This is a desirable feature when we are

25   dealing with bursty TCP traffic in presence of congestion. Finally, sliding window samples are exponentially averaged in order to obtain a smoothed bandwidth share estimate over time. A simple exponential averaging filter to calculate the Rate Estimate at the instant the kth ACK is received is given by the

30   equation in FIG. 4.

BE is more effective than RE as an estimate in environments with random error. On the other hand, the RE method appears to be more appropriate when packet losses are because of congestion (router buffer overflow). Based on the tradeoff presented above,

35   a hybrid method that combines both sampling strategies would be

of interest, provided one can determine the cause of packet loss: errors or buffer overflow. This issue of course is beyond the sampling methodology investigation itself. In fact, if a sender were able to distinguish with certainty between error and buffer overflow losses, the sender reaction to the former would be to retransmit immediately with no change of window size.

The following method may be used to determine the predominant cause of packet loss requiring no assistance from layers below TCP. The method is herein termed Combined Rate and Bandwidth estimation (CRB). The CRB method uses the relationship between the current cwin value and the estimated pipe size, the latter indicated by the product of RE and the minimum RTT. When RE * RTTmin is significantly smaller than cwin, it is more likely that packet losses are due to congestion. This is because the connection is using a cwin value much higher than its share of pipe size, thus congestion is likely. In CRB, whenever a packet loss is indicated, the sender determines the predominant cause of loss as follows: when the ratio RE *RTTmin to cwin exceeds a threshold value θ, the use of RE is indicated. Below θ, BE is indicated. A threshold of $\theta=1.4$ was found to give the satisfactory results.

A packet loss is indicated either by a reception of 3 DUPACKs or a coarse timeout. The CRB method sets ssthresh and cwin after a packet loss indicated by three duplicate ACKs. Referring now to FIG. 5, a psuedo-code listing is presented for the CRB method. In the pseudo-code, seg_size identifies the length of a TCP segment in bits. The value RTTmin is set as the smallest RTT estimated by TCP, using its own RTT estimation method. Note that the basic Reno behavior is still captured, while setting ssthresh to the value of BE or RE, as appropriate, provides a more rational recovery.

In another aspect of the invention, the TCP sender Adaptively determines a Bandwidth Share Estimate (TCP-ABSE).

As such, TCPW ABSE is then a sender-only modification of TCP
NewReno. The estimate is based on information in the ACKs, and
5   the rate at which the ACKs are received. After a packet loss
indication, which could be due to either congestion or link
errors, the sender uses the estimated bandwidth to properly set
the congestion window and the slow start threshold.

FIG. 7 is a pseudocode listing for a TCP control process
10   using an adaptive bandwidth share estimate in accordance with an
exemplary embodiment of the present invention. In TCP-ABSE, a
sender determines a connection bandwidth estimate as mentioned
above and uses it to set cwin and ssthresh after a packet loss
indication. The rationale of the algorithm above is that after
15   a timeout, cwin and the ssthresh are set equal to 1 and ABSE,
respectively. Thus, the basic Reno behavior is still captured,
while a reasonably speedy recovery is ensured by setting ssthresh
to the value of ABSE.

An Adaptive Bandwidth Share Estimation (ABSE) process adapts
20   to the congestion level in performing its bandwidth sampling, and
employs a filter that adapts to the round trip time and to the
rate of change of network conditions. The bandwidth estimation
is   computed   using   a   time   varying   coefficient,
Exponentially-Weighted Moving Aaverage (EWMA) filter, which has
25   both adaptive gain and adaptive sampling.

FIG. 8 is a data flow diagram depicting an adaptive
bandwidth share estimation process in accordance with an
exemplary embodiment of the present invention. An ACK stream is
received by the process and used to generate a recent throughput
30   sample. The recent throughput is used in conjunction with an
expected throughput to generate a sampling time interval. The
time interval is then used in conjunction with the ACK stream to
generate an unfiltered bandwidth share sample. The unfiltered
bandwidth share sample is used to generate a network instability
35   measure which is filter to generate a filter gain. The filter

-11-

gain is used in conjunction with the unfiltered bandwidth share sample to generate a filtered adaptive bandwidth share estimate.

5   The equations governing the functional blocks described above are given in Appendix C, the contents of which are hereby incorporated by reference as if stated fully herein. A specific implementation of the present invention is described in Appendix D, the contents of which are hereby incorporated by reference as

10 if stated fully herein.

FIG. 6 is a block diagram of a computing device suitable for hosting a transmission protocol control process in accordance with an exemplary embodiment of the present invention. A host includes a processor coupled via a bus to a memory device, a

15 storage device controller, and a network device controller. The processor uses the network device controller to control the operations of a network device which is adapted for communications using a transport protocol to transmit data to a receiver across a connection through a computer network.

20 The storage controller is coupled to a storage device having a computer readable storage medium for storage of program instructions executable by the processor. The program instructions are stored in the storage device until the processor retrieves the program instructions and stores them in the memory.

25 The processor then executes the program instructions stored in memory to implement the transport protocol control process as previously described.

Although this invention has been described in certain specific embodiments, many additional modifications and

30 variations would be apparent to those skilled in the art. It is therefore to be understood that this invention may be practiced otherwise than as specifically described. Thus, the present embodiments of the invention should be considered in all respects as illustrative and not restrictive, the scope of the invention

35

1   50333/FLC/R268

to be determined by claims supported by this application and the
claims' equivalents rather than the foregoing description.

5

10

15

20

25

30

35

-13-

ABSTRACT OF THE DISCLOSURE

A refinement of TCP Westwood allowing the management of the Efficiency/Friendliness-to-NewReno tradeoff is provided. TCP Westwood implements a novel congestion window control method based on available bandwidth estimation. The original TCP Westwood sampling strategy that produces available Bandwidth Estimates (BE) is combined with a new strategy that produces Rate Estimates (RE). The new strategy is called Combined Rate and Bandwidth estimation (CRB). To use CRB, a connection first infers the predominant cause of packet losses, and then uses the most appropriate estimation method.

PROVISIONAL APPLICATION COVER SHEET [37 CFR 1.53(c)]

This is a request for filing a PROVISIONAL APPLICATION under 35 U.S.C. §111(b) and 37 CFR 1.51(a)(2)

Date   :   May 28, 2003
Docket No.   :   50333/FLC/R268
EXPRESS MAIL NO. EV 352374704 US

Mail to: Mail Stop PROVISIONAL PATENT APPLICATION

INVENTOR(S)/APPLICANT(S) (LAST NAME, FIRST NAME, MIDDLE INITIAL, RESIDENCE (CITY AND EITHER STATE OR FOREIGN COUNTRY)

   Gerla, Mario, Santa Monica, California and Sanadidi, M. Yahya , Santa Monica, California

_____   Additional inventors are being named on separately numbered sheets attached hereto.

TITLE OF THE INVENTION (280 characters max)

   TCP WINDOW CONGESTION CONTROL

APPLICANT(S) STATUS UNDER 37 CFR § 1.27

__X__   Applicant(s) and any others associated with it/them under § 1.27(a) are a SMALL ENTITY

ENCLOSED APPLICATION PARTS

__14__   Specification (number of pages)
__6__   Drawings (number of sheets)
_____   Assignment
__X__   Other (specify): Appendices A-D

FEE AND METHOD OF PAYMENT

__X__   A check for the filing fee of $ _80.00_   is enclosed.
   The Commissioner is hereby authorized to charge any fees under 37 CFR 1.16 and 1.17 which
   may be required by this filing to Deposit Account No. 03-1728. Please show our docket number
   with any charge or credit to our Deposit Account. **A copy of this letter is enclosed.**

_____   No filing fee enclosed.

The Invention was made by an agency of the United States Government or under a contract with an
agency of the United States Government.

_____   No   __X__   Yes, the name of the U.S. Government agency and the Government contract
                  number are: ANI-9983138

Please address all correspondence to **CHRISTIE, PARKER & HALE, LLP, P.O. Box 7068, Pasadena,
CA 91109-7068, U.S.A.**

Respectfully submitted,

CHRISTIE, PARKER & HALE, LLP

By _____
   Frank L. Cire
   Reg. No. 42,419
   626/795-9900

PROVISIONAL APPLICATION FILING ONLY

FLC/sd
SD PAS506708.1-*-5/28/03 8:11 AM

$$RE_k = \frac{\sum\limits_{t_j > t_k - 1 - T} d_j}{T}$$

FIG. 1

$$RE_{k-1} = \frac{\sum\limits_{t_j > t_k - 1 - T} d_j}{T}$$

FIG. 2

$$RE_k = RE_{k-1} + \frac{d_k - \dfrac{\sum_{t_i < t_k,\, t_{i_2} > t_{k-1} - T} d_i}{T}}{T}$$

FIG. 3

$$RE_k = \frac{19}{21}\hat{RE}_{k-1} + \frac{1}{21}\left(RE_k + RE_{k-1}\right)$$

FIG. 4

```
if (3 DUPACKs are received)
    if (cwin/ ((RE * RTTmin) / seg_size) >θ) /*Congestion condition*/
        ssthresh = (RE* RTTmin) / seg_size;
    else /* no congestion */
        ssthresh = (BE * RTTmin) / seg_size;
    endif
    if (cwin > ssthresh) /* congestion avoid. */
        cwin = ssthresh;
    endif

endif
```

FIG. 5
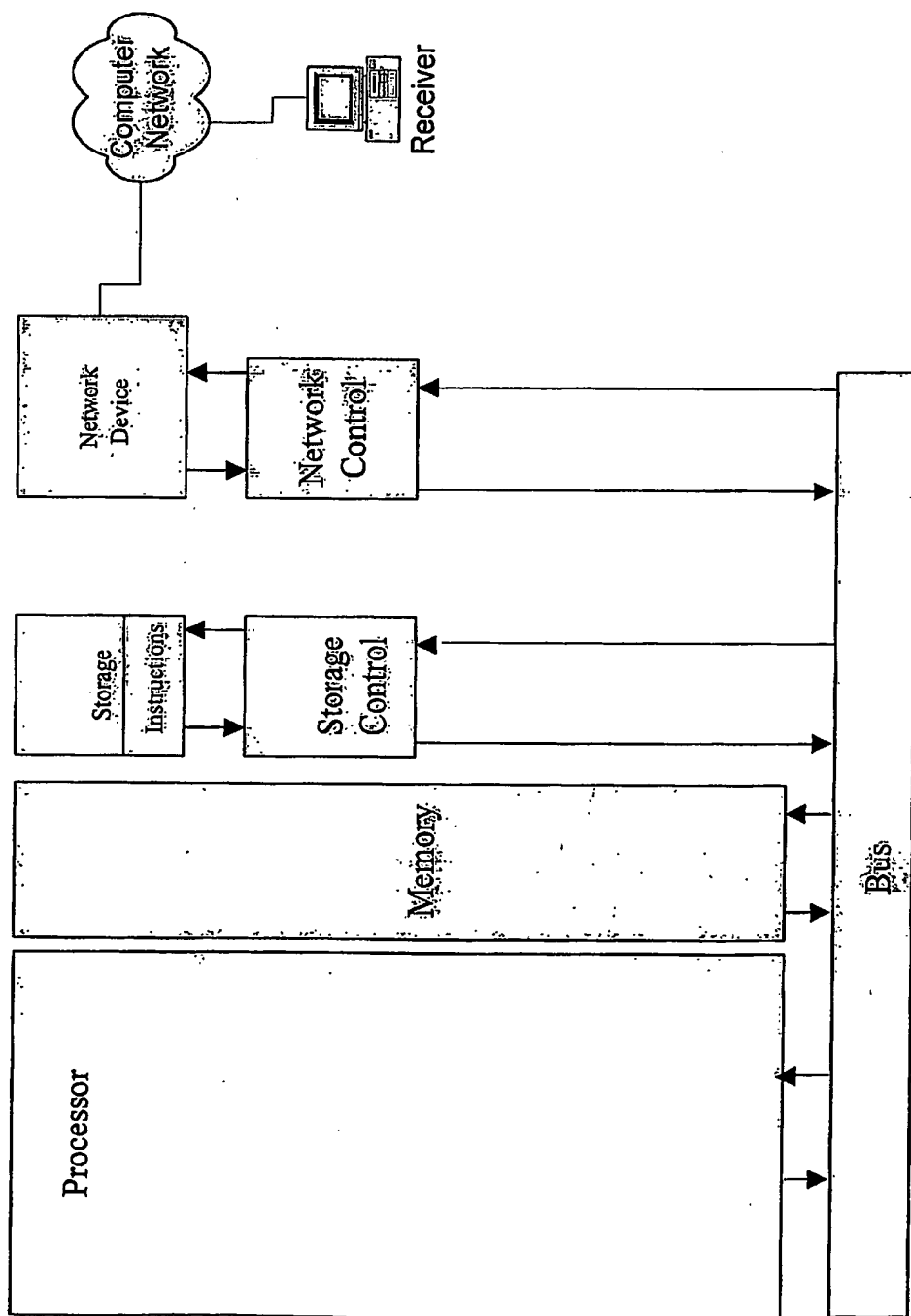
FIG. 6

```
if (3 DUPACKs are received)
    ssthresh = (ABSE * RTTmin) / seg_size;
    if (cwin > ssthresh) /* congestion avoid. */
        cwin = ssthresh;
    endif
endif
```

In case a packet loss is indicated by a timeout expiration, *cwin* and *ssthresh* are set as follows:

```
if (coarse timeout expires)
    cwin = 1;
    ssthresh = (ABSE * RTTmin) / seg_size;
    if (ssthresh < 2)
        ssthresh = 2;
    endif
endif
```
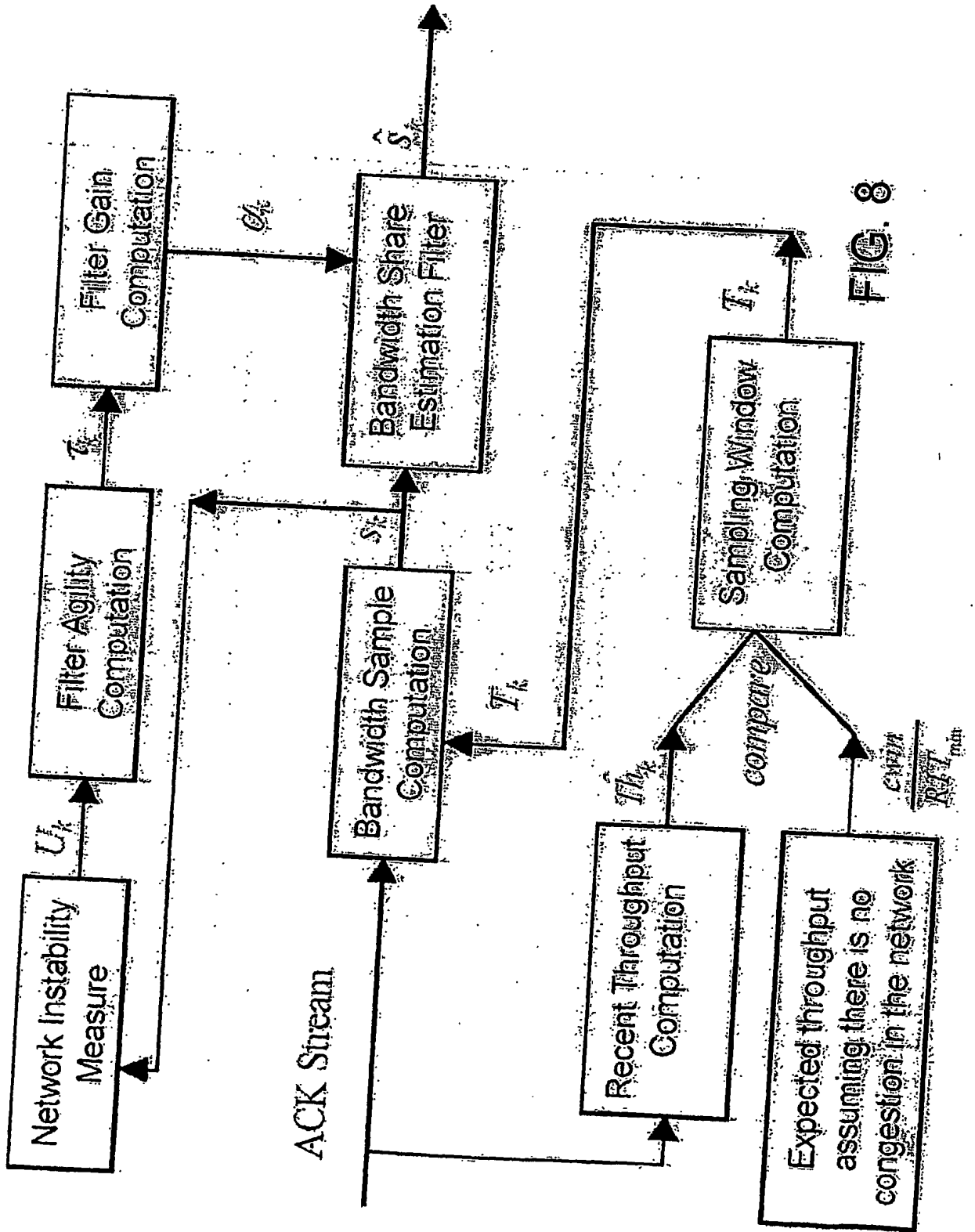
FIG. 7

Network Instability Measure

Filter Agility Computation

Filter Gain Computation

Bandwidth Sample Computation

Bandwidth Share Estimation Filter

Sampling Window Computation

Recent Throughput Computation

Expected throughput assuming there is no congestion in the network

ACK Stream

U_k

T_k

G_k

S_k

$\hat{S}_k$

T_k

T_k

$\hat{Th}_k$

$compare$

$\dfrac{cwin}{RTT_{min}}$

FIG. 8